

SINGLE LEPTOQUARK PRODUCTION AT TeV ENERGY γp
COLLIDERS

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Abstract

The resolved and direct photon contributions to the single leptoquark (L) production process $\gamma p \rightarrow Le$ are analysed for both scalar (S) and vector (V) leptoquarks in detail. It is shown that resolved photon contribution dominates for $M_L \leq 300 GeV$. For $M_V \geq 1 TeV$ and $M_S \geq 0.5 TeV$ cross section is completely determined by the direct photon contribution. The vector leptoquarks are discussed for both gauge- and non-gauge cases separately.

1 Introduction

The theories beyond the Standard Model (SM) such as composite models[1], grand unified theories[2], and E_6 superstring-inspired models[3] predict the existence of leptoquarks carrying baryon and lepton numbers simultaneously and having the electric charges $\pm 5/3$; $\pm 4/3$; $\pm 2/3$ and $\pm 1/3$ [4].

The production and possibility of the detection of leptoquarks have been analysed in detail for, for instance, ep [5-7], hadronic [8], and e^+e^- colliders [4,9]. It is well known that high energy ep colliders can be converted into a high energy γp collider with the help of backscattered laser beams [10]. The single and double leptoquark production in γp colliders are also analysed in the literature [11,12] without taking the hadronic structure of photon into account. Namely they neglected the resolved photon contribution. Furthermore in these works the distribution of quarks and gluons in the proton are described by a Q^2 independent parametrisation which may be misleading since the c.m. energy for each subprocess supporting $\gamma p \rightarrow Le$ is not identical. In this work we shall analyse the production of vector ($L = V$) and scalar leptoquarks ($L = S$) in γp colliders by considering the resolved photon contribution as well.

The article is organized as follows: Section 2 describes the theoretical basis and Section 3 is devoted to the numerical analysis and discussions.

2 Total Cross Section for $\gamma p \rightarrow Le$ Scattering

The production of leptoquarks in γp collisions can occur either by direct or resolved photon processes. In the latter case photon interacts with the proton through its hadronic components. It is clear that the following processes are

responsible for the $\gamma p \rightarrow Le$ scattering:

$$\begin{aligned}\gamma q &\rightarrow Le \\ \gamma g &\rightarrow Le\end{aligned}\tag{1}$$

$$\begin{aligned}\gamma_q g &\rightarrow Le \\ \gamma_g q &\rightarrow Le\end{aligned}\tag{2}$$

where processes in (1) defines the direct photon scattering and those in (2) defines resolved photon scattering.

The complete $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant Lagrangian in the low energy range ($M_L \approx 1TeV$), conserving baryon (B) and lepton (L) numbers, is given by [4]

$$L = L_{F=2}^f + L_{F=0}^f + L^{scalar} + L^{vector}\tag{3}$$

where $F = |3B + L|$. The first two terms in the lagrangian are given by the following expressions

$$\begin{aligned}L_{F=2}^f &= g_1(\bar{q}_L^c i\tau_2 l_L + \bar{u}_R^c e_R)S_1 \\ &+ \tilde{g}_1 \bar{d}_R^c e_R \tilde{S}_1 + g_3 \bar{q}_L^c i\tau_2 \vec{\tau} l_L \cdot \vec{S}_3 \\ &+ g_2(\bar{d}_R^c \gamma^\mu l_L + \bar{d}_L^c \gamma^\mu e_R)V_{2\mu} \\ &+ \tilde{g}_2 \bar{u}_R^c \gamma^\mu l_L \tilde{V}_{2\mu} + h.c.\end{aligned}\tag{4}$$

$$\begin{aligned}L_{F=0}^f &= h_2(\bar{q}_L i\tau_2 e_R + \bar{u}_R l_L)R_2 \\ &+ \tilde{h}_2 \bar{d}_R l_L \tilde{R}_2 + h_3 \bar{q}_L \vec{\tau} l_L \cdot \vec{U}_3 \\ &+ h_1(\bar{q}_L \gamma^\mu l_L + \bar{d}_R \gamma^\mu e_R)U_{1\mu} \\ &+ \tilde{h}_1 \bar{u}_R \gamma^\mu e_R \tilde{U}_{1\mu} + h.c.\end{aligned}\tag{5}$$

In $L_{F=0}^f$ and $L_{F=2}^f$ there exist various kinds of leptoquarks interacting with leptons and quarks. Here q_L and l_L are $SU(2)_L$ left handed quark and lepton doublets, $\psi^c = C\bar{p}\bar{s}i^T$ is the charge conjugated fermion field. Among vector leptoquarks, U_1, \tilde{U}_1 are $SU(2)_L$ singlets, V_2, \tilde{V}_2 are left handed $SU(2)_L$ doublets, and \vec{U}_3 is $SU(2)_L$ triplet. Among scalar leptoquarks, S_1, \tilde{S}_1 are $SU(2)_L$ singlets, R_2, \tilde{R}_2 are left handed $SU(2)_L$ doublets, and \vec{S}_3 is $SU(2)_L$ triplet. Note that there are certain constraints on the leptoquark masses and coupling constants from low energy experiments, which follows, for instance, from the absence of $FCNC$ at the tree level, and from $D^0 - \bar{D}^0$ and $B^0 - \bar{B}^0$ mixings [13-16].

L^{scalar} in the Lagrangian describes the interaction of scalar leptoquarks with the neutral gauge bosons, and is given by

$$L^{scalar} = \sum_i [(D_\mu S^i)^\dagger (D^\mu S^i) - M_S^2 S^\dagger S] \quad (6)$$

where S^i is the i -th scalar leptoquark field and $D_\mu = \partial_\mu - ieA_\mu - ig_s \frac{\lambda^a}{2} A_\mu^a$ is the covariant derivative.

Unlike the scalar leptoquark case, $VV\gamma$ and VVg vertices involve an ambiguity depending on the nature of vector leptoquarks. For example, if the vector leptoquarks are gauge bosons of an extended gauge group, then the trilinear vertices are completely and unambiguously fixed by the gauge invariance. When they are not gauge bosons, then the vector leptoquark lagrangian can be regarded as an effective theory. It is clear that in this effective theory there are many free parameters. In order to restrict the number of these parameters, in addition to $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance and B and L conservations, we impose the CP invariance in the effective lagrangian. Moreover we restrict ourselves to operators of dimensionality 4 or less. There is only one operator $ig\kappa V^\mu V_{\mu\nu} V^\nu$ complying with these condi-

tions and it describes the anomalous magnetic moment contribution to the trilinear vertex.

Thus the effective gauge boson- vector leptoquark lagrangian L^{vector} conserving CP and containing operators of dimension 4 or less is given by (see, for example, [17])

$$\begin{aligned}
L^{vector} = & \sum_i \left\{ -\frac{1}{2} V_{i\mu\nu}^\dagger V^{i\mu\nu} + M_V^2 V_{i\mu}^\dagger V^{i\mu} \right. \\
& \left. - i \sum_{j=\gamma,g} g_j \kappa_j V_{i\mu} G^{j\mu\nu} V_{i\nu} \right\}
\end{aligned} \tag{7}$$

where i runs over all vector leptoquarks, $V_{\mu\nu} = D_\mu V_\nu - D_\nu V_\mu$ is the leptoquark field strength and $G_{j\mu\nu}$ is the field strength tensor of photon ($j = \gamma$) or gluon ($j = g$). In what follows we shall take anomalous couplings of photon and gluon identical; $\kappa_\gamma = \kappa_g = \kappa$.

One can readily obtain the Feynman rules for trilinear vertices immediately from L^{vector}

$$\begin{aligned}
VV \left\{ \begin{matrix} \gamma \\ g \end{matrix} \right\} = & \left\{ \begin{matrix} ieQ \\ ig_s \frac{\lambda^a}{2} \end{matrix} \right\} \{ (k_2 - k_3)_\mu g_{\alpha\beta} + (k_3 - \kappa k_1)_\alpha g_{\mu\beta} \\
& + (k_1(1 + \kappa) - k_2)_\beta g_{\mu\beta} \}
\end{aligned} \tag{8}$$

where all momenta are incoming. Here k_1, k_2 and k_3 are the 4- momenta of photon (gluon) and leptoquarks respectively. We will next turn our attention to the calculation of the cross section for $\gamma p \rightarrow Le$ scattering.

The total cross section for $\gamma p \rightarrow Le$ scattering has the form

$$\sigma(\gamma p \rightarrow Le) = \sigma_{dir}(\gamma p \rightarrow Le) + \sigma_{res}(\gamma p \rightarrow Le) \tag{9}$$

where σ_{dir} and σ_{res} represent the contributions of the direct and resolved photons respectively. The total cross section for the leptoquark production by direct photon interaction can be obtained by folding the cross section for

the elementary process (1) with the the photon distribution in electron and quark distribution in the proton:

$$\sigma_{dir}(\gamma p \rightarrow Le) = \int_{\lambda}^{0.83} dx \int_{\frac{\lambda}{x}}^1 dy f_{\gamma/e}(x) f_{q/p}(y, \frac{xy s}{2}) \sigma_{\gamma q}(xys) \quad (10)$$

In the same manner, the total cross section for leptoquark production by resolved photon contribution can be obtained by folding the cross section of the elementary process (2) with quark (gluon) distribution in the photon, gluon (quark) distribution in the proton and photon distribution in the electron:

$$\begin{aligned} \sigma_{res}(\gamma p \rightarrow Le) = & \int_{\lambda}^{0.83} dx \int_{\frac{\lambda}{x}}^1 dy \int_{\frac{\lambda}{xy}}^1 dz f_{\gamma/e}(x) [f_{g/\gamma}(y, \frac{xy s}{2}) f_{q/p}(z, \frac{xyz s}{2}) \\ & + f_{q/\gamma}(y, \frac{xy s}{2}) f_{g/p}(z, \frac{xyz s}{2})] \sigma_{gq}(xyzs) \end{aligned} \quad (11)$$

In (10) and (11) $f_{a/b}(x, Q^2)$ is the Q^2 dependent distribution function of the parton a in the hadron b ($f_{\gamma/e}(x)$ is an exception). In all these functions we have set $Q^2 = \frac{\hat{s}}{2}$ where \hat{s} is the invariant mass flow to the subprocess under concern, \sqrt{s} is the c.m. energy of the collider and $\lambda = (M_L + m_q)^2/s$, where M_L and m_q are the leptoquark and quark masses respectively.

Let us now discuss the construction of the formulae (10) and (11) in the case of $\gamma_g q \rightarrow Le$, as an example. Here s is the c.m. energy squared of ep collider. Only fraction x of s enters the γp system, so $s_{\gamma p} = xs_{ep}$, $0 \leq x \leq 1$. Now hadronic components of photon mediate some fraction y of $s_{\gamma p}$, so $s_{gp} = ys_{\gamma p}$, $0 \leq y \leq 1$. Similarly, quark coming off the proton takes away some fraction z of s_{gp} so $s_{gq} = zs_{gp}$, $0 \leq z \leq 1$.

The total cross section of the elementary subprocess (1) is given by

$$\begin{aligned} \sigma_{\gamma q}^V = & A_{\gamma} \{ \ln(\frac{a-1}{b}) [4q_2^2 - 8a(a-1)q_2(q_3 - q_1)] \\ & + \ln a [4q_3q_1(\kappa + 1) + q_3^2(\kappa^2 + 6\kappa + 1) + 8aq_3(q_3 + a(q_1 - q_2))] \} \end{aligned} \quad (12)$$

$$\begin{aligned}
& + \frac{q_3(\kappa - 1)}{a} \{2(q_2 + q_1) - q_3(\kappa + 1)\}] \\
& + 8a^2 \{q_2 q_1 - 8q_3(q_3 + q_1) + 2q_1^2\} + a \{q_2^2 - q_2 q_3(\kappa + 1) - 6q_2 q_1 \\
& + (1/4)q_3^2 \kappa(\kappa + 2) + (33/4)q_3^2 - q_3 q_1(-5\kappa + 3) - 3q_1^2\} \\
& + \frac{1}{a} \{q_2^2 + q_2 q_3(\kappa - 3) + 2q_2 q_1 + (1/4)q_3^2(\kappa^2 + 26\kappa + 9) \\
& + q_3 q_1(\kappa - 3) + q_1^2\} - 2q_2^2 + 4q_2 q_3 - 4q_2 q_1 - (1/2)q_3^2(\kappa^2 + 14\kappa + 5) \\
& + 4q_3 q_1(\kappa + 2)\}
\end{aligned}$$

and

$$\begin{aligned}
\sigma_{\gamma q}^S &= A_\gamma \left\{ \ln \left(\frac{1-a}{b} \right) [2a(a-1)q_2(q_1 - q_3) + q_2^2] \right. \\
&+ \ln a [2aq_3 \{q_3 + a(q_1 + q_2)\}] + a^2 \{ (1/2)q_1^2 - 2q_1 q_2 \\
&- 2q_1 q_3 - 2q_3^2 \} + a \{ -q_1^2 + 4q_1 q_2 + 2q_1 q_3 + 2q_3^2 \} \\
&+ \left. (1/2)q_1^2 - 2q_1 q_2 \right\}
\end{aligned} \tag{13}$$

where superscripts V and S refer to the vector and scalar leptoquark productions respectively. In (4) and (5) $a = M_L^2/s$, $b = m_q^2/s$, $q_1 = q$, $q_2 = 1$, $q_3 = q + 1$ (q quark charge), and κ is the anomalous coupling of leptoquarks to photon and gluon [17]. The factor A_γ is given by

$$A_\gamma = \frac{\pi \alpha^2}{2s}. \tag{14}$$

The crosssections σ_{gq}^V and σ_{gq}^S could be obtained from (4) and (5) with the following replacements:

$$\sigma_{gq}^{V,S} = \sigma_{\gamma q}^{V,S}(q_1 = 1, q_2 = 0, q_3 = 1, A_\gamma \rightarrow A_g) \tag{15}$$

where

$$A_g = \frac{\pi \alpha \alpha_s}{12s}. \tag{16}$$

and α_s is given by

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2f) \ln Q^2/\Lambda^2} \quad (17)$$

up to one-loop accuracy.

Now, let us consider the large s behaviour of the cross section for the subprocess in (1) for the arbitrary values of κ . From (12) one can easily obtain

$$\sigma_{\gamma q}^V = \frac{\pi\alpha^2(q+1)^2}{M_V^2} \left[\frac{1}{2} \ln \frac{s}{m_V^2} (\kappa - 1)^2 + \frac{1}{8} (\kappa^2 + 30\kappa + 1) \right] \quad (18)$$

in the limit $s \gg M_V^2$. We see that for $\kappa \neq 1$ the cross section grows logarithmically. This is due to the t -channel contribution. As we noted before, if V is a non-gauge particle ($\kappa \neq 1$) this logarithmic dependence can be considered as the low energy manifestation of a more fundamental theory at a higher energy scale. So, according to the effective theory description, the behaviour of the cross section is acceptable as long as energy is sufficiently low. At high energies, the effective theory is superseded by a more fundamental theory, where the increase of the cross section with s is stopped and unitarity is preserved. If V has the gauge nature (where $\kappa = 1$), the cross section reaches the constant value

$$\sigma_{\gamma q}^V = \frac{4\pi\alpha^2(q+1)^2}{M_V^2} \quad (19)$$

which is similar to the single W boson production in the reaction $\gamma p \rightarrow WX$ [17] in the standard model.

After giving the expression for subprocess cross sections we now turn to the explicit expressions for the distribution functions in (10) and (11).

The function $f_{\gamma/e}(x, Q^2)$ is the energy spectrum of the backscattered laser

photons [10]

$$f_{e/\gamma}(x) = \frac{1}{D(\zeta)} \left[1 - x + \frac{1}{1-x} - \frac{4x}{\zeta(1-x)} + \frac{4x^2}{\zeta^2(1-x)^2} \right] \quad (20)$$

where

$$D(\zeta) = \left(1 - \frac{4}{\zeta} - \frac{8}{\zeta^2} \right) \ln(1-\zeta) \frac{1}{2} + \frac{8}{\zeta} - \frac{1}{2(1+\zeta)^2} \quad (21)$$

with $\zeta = 4.82$. The maximum value of x is found as $x_{max} = \frac{\zeta}{\zeta+1} = 0.83$ which is the upper limit of the x integral in (2) and (3).

In describing the quark and gluon distributions in the proton we shall use the results of [18] where a Q^2 dependent parametrisation is given. We shall not reproduce all the details of the parametrisations here, instead we summarize the general form of the functions and refer the reader to the references for details. $f_{q/p}(x, Q^2)$ parametrizes the quark (sea plus valence) distributions in the proton

$$xf_{q/p}(x, Q^2) = N \frac{A_2}{B(A_3 + 1, A_1/A_2)} x^{A_1} (1 - x^{A_2})^{A_3} \quad (22)$$

$$+ A_4(1 + A_5x + A_6x^2)(1 - x)^{A_7} + A_8e^{-A_9x} \quad (23)$$

where $B(x, y)$ is the Euler's Beta function, N equals 2 for u quark and 1 for d quark. The coefficients A_i ($i=1, \dots, 9$) are tabulated in [18] and they are explicit functions of

$$\bar{s} = \ln \left\{ \frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)} \right\} \quad (24)$$

where $Q_0^2 = 4GeV^2$ and $\Lambda = 0.4GeV$.

The gluon distribution in the proton is parametrised by $f_{g/p}$ having the expression [18]

$$xf_{g/p}(x, Q^2) = B_1(1 + B_2x + B_3x^2)(1 - x)^{B_4} + B_5e^{-B_6x} \quad (25)$$

and again the coefficients B_i are functions of \bar{s} and are tabulated in [18].

For the gluon and quark distributions in the photon we shall use the Q^2 dependent parametrisation given in [19]. The quark distribution in the photon is parametrised by $f_{g/\gamma}(x, Q^2)$ which is given by

$$xf_{g/\gamma}(x, Q^2) = C_1 x^{C_2} (1-x)^{C_3} \quad (26)$$

where the coefficients C_i are functions of

$$t = \ln(Q_0^2/\Lambda^2)e^{\bar{s}} \quad (27)$$

and are tabulated in [19].

The quark distribution (sea plus valence) in the photon is parametrised by

$$f_{q/\gamma}(x, Q^2) = A_f q_v(x, Q^2) + B_f q_s(x, Q^2) \quad (28)$$

where the coefficients A_f and B_f [19] change as the number of flavours f changes (in connection with the momentum scale Q^2) and the functions $q_v(x, Q^2)$ and $q_s(x, Q^2)$ (q_{NS}^γ and Σ^γ respectively, in the notation of [19]) are given by

$$xq_j(x, Q^2) = x \frac{x^2 + (1-x)^2}{D_{1j} - D_{2j} \ln(1-x)} + D_{3j} x^{D_{4j}} (1-x)^{D_{5j}} \quad (29)$$

where $j = v, s$, and the coefficients D_{ij} ($i = 1..5, j = v, s$) are given in [19].

3 Numerical Analysis

We will now analyze the total cross section $\sigma(\gamma p \rightarrow Le)$ defined in (9) for vector and scalar leptoquarks. We based our analysis only to the first generation so that the quark entering the scattering process is either u or d ,

producing in the final state leptoquarks of electromagnetic charge $5/3$ or $2/3$ [4] respectively. Although there are many accelerators [11,12] deserving analysis under such a work, for our purpose it is sufficient to analyze a single accelerator which we choose to be $LHC + TESLA$ with $\sqrt{s} = 5.5 TeV$.

Fig.1 and Fig.2 show the total cross section in (9), at $\sqrt{s} = 5.5 TeV$, for $V_{5/3}$ (gauge particle) and $S_{5/3}$ respectively. We give Fig.1 and Fig.2 to demonstrate the relative magnitude of the direct and resolved photon contributions as the leptoquark mass changes. These two are typical examples applicable to all other cases. From Fig. 1 and Fig. 2 we see that for $M_L \leq 300 GeV$ the total cross section in (9) is strongly dominated by resolved photon contribution in (11). Moreover, Fig. 1 and Fig. 2 show, respectively, that for $M_V \geq 1 TeV$ and $M_S \geq 0.5 TeV$ the total cross section in (9) is completely determined by the direct photon contribution in (10). We see that the leptoquark mass range where the resolved photon contribution is non negligible is within the mass bounds given in [17]; thus, the effects of the hadronic component of photon in γp colliders are directly observable in future experiments.

Fig. 3 shows the dependence of the total cross section in (12) on M_V for different values of κ . From this figure we see that for non- gauge V , the cross section in (12) is considerably enhanced (suppressed) as κ grows (falls) to higher (lower) values from unity. Especially the $\kappa \geq 1$ case is interesting, because enhancement in the cross section is large for low values of M_V where the resolved photon contribution dominates. Lastly, we observe from this figure that the cross section for $V_{5/3}$ is always larger than that for $V_{2/3}$.

Finally, in Fig.4 we show the variation of the total cross section in (13) with M_S . We conclude from this figure that the total cross section for $S_{5/3}$ is always larger than that for $S_{2/3}$ (see also [11,12]).

In conclusion, we have discussed the single leptoquark production in γp

colliders for scalar and vector leptoquarks. We have analysed the contribution of the hadronic component of the photon to the total cross section. Moreover, gauge- and non- gauge- vector leptoquarks are discussed separately in terms of their contribution to the total cross section.

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Figure 1: For $V_{5/3}$ (gauge particle) at $\sqrt{s} = 5.5TeV$, contributions of resolved photon (dashed) and direct photon (short-dashed) to the total crosssection (solid).

Figure 2: The same as in Fig. 1 but for $S_{5/3}$

Figure 3: Variation of the total crosssection for vector leptoquarks as a function of leptoquark mass for different values of anomalous coupling. Here circle, square and triangle corresponds to $\kappa = 0.5$, $\kappa = 1.0$ and $\kappa = 2.0$ respectively.

Figure 4: Variation of the total crosssection for scalar leptoquarks as a function of leptoquark mass.

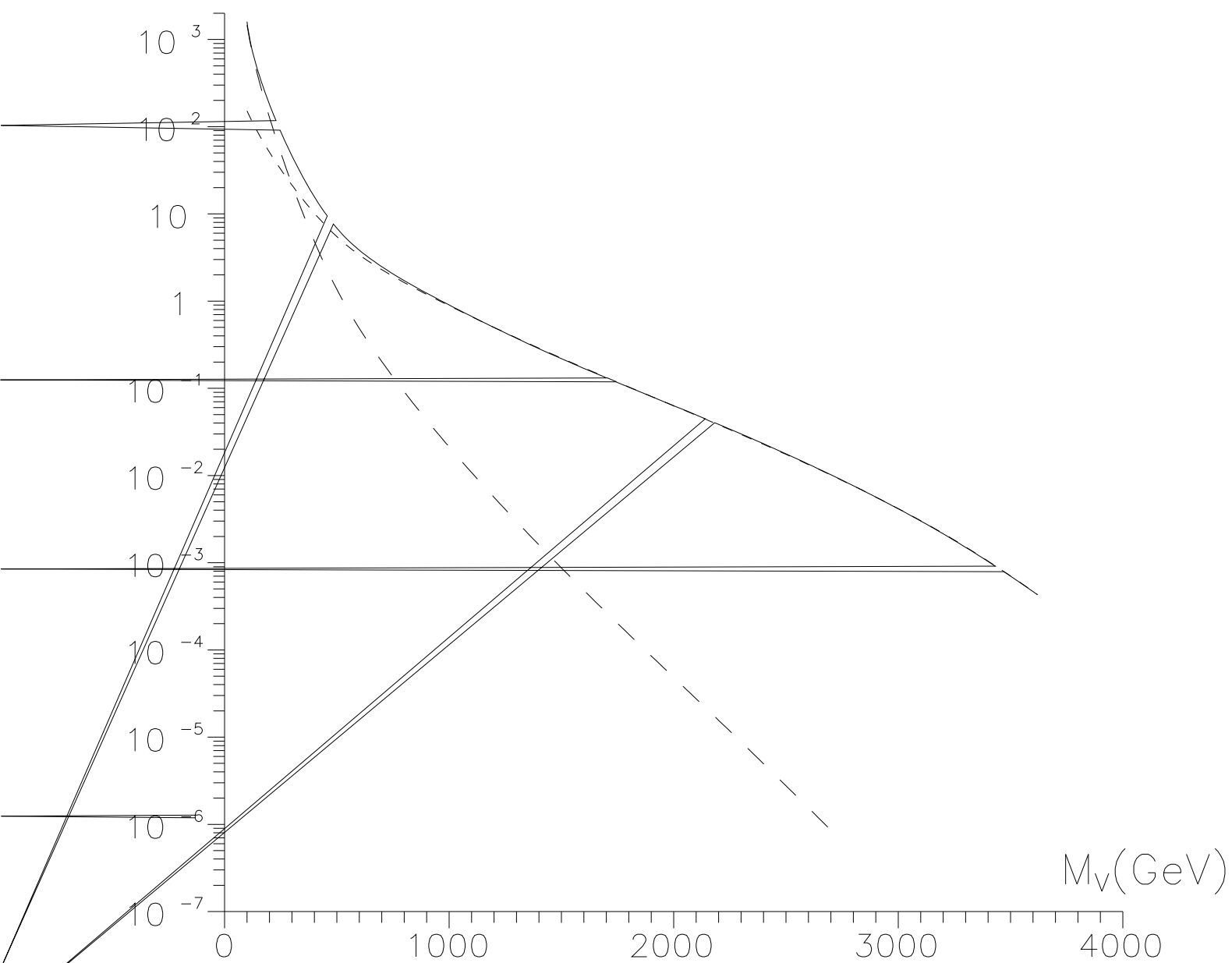


FIG. 1

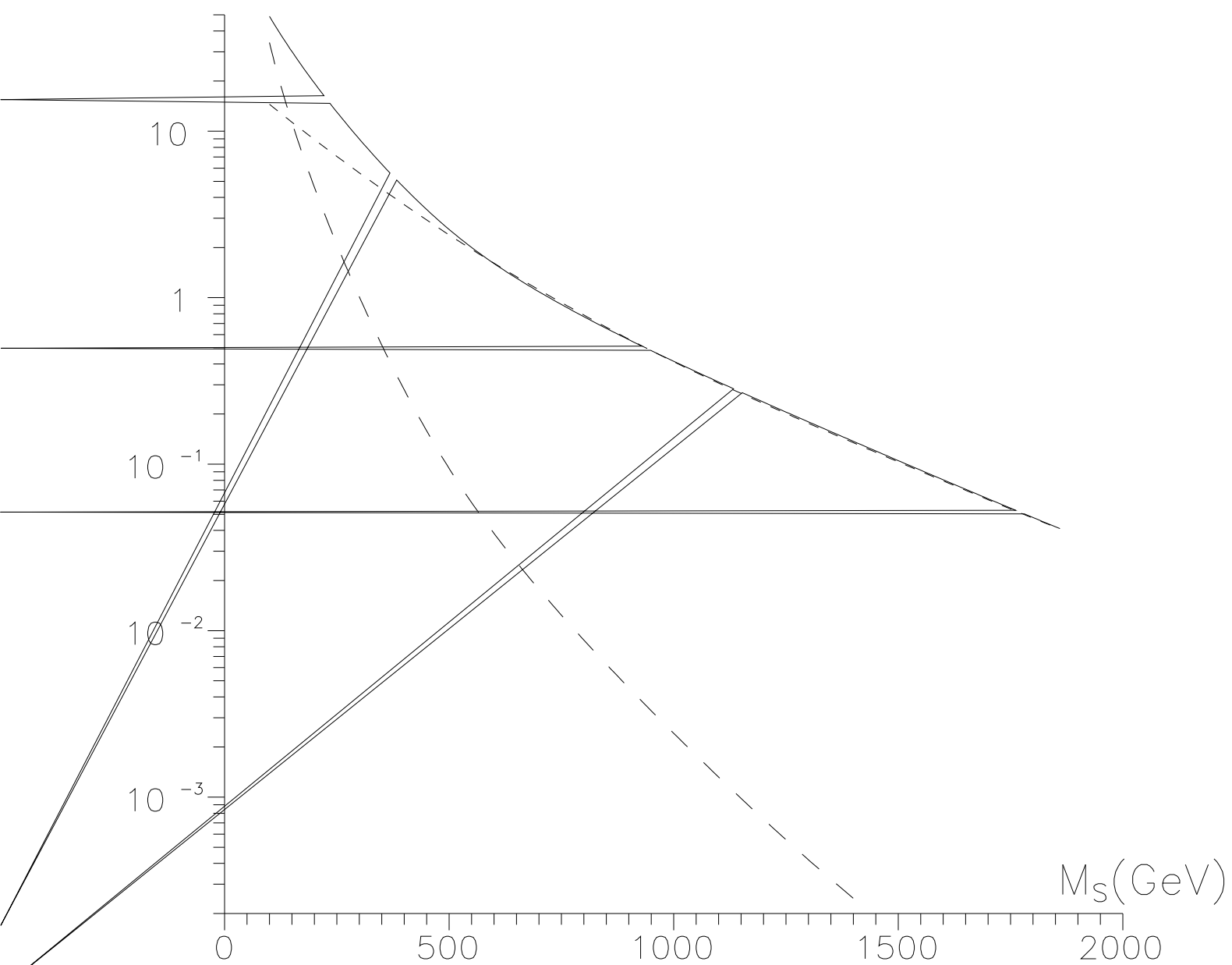


FIG. 2

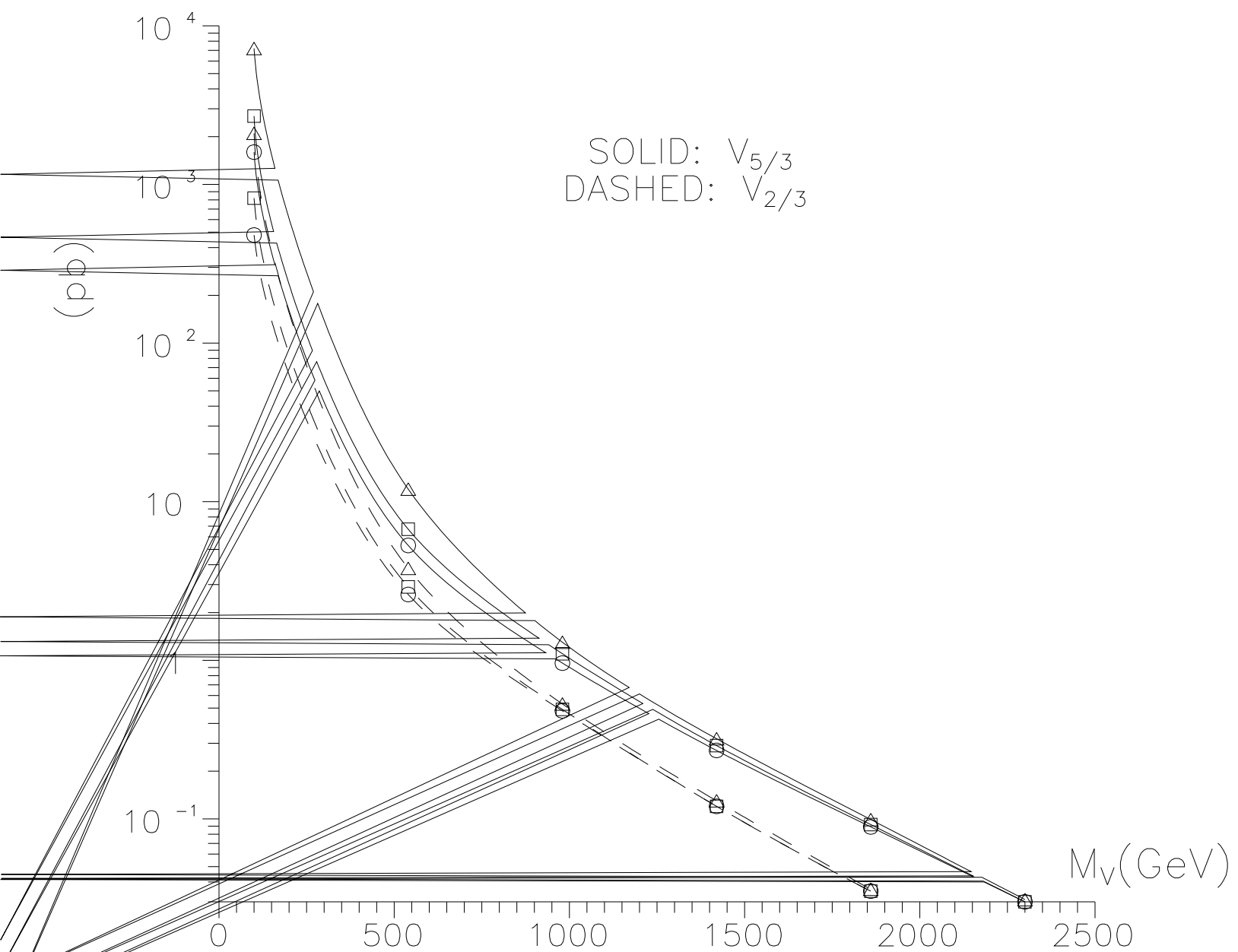


FIG. 3

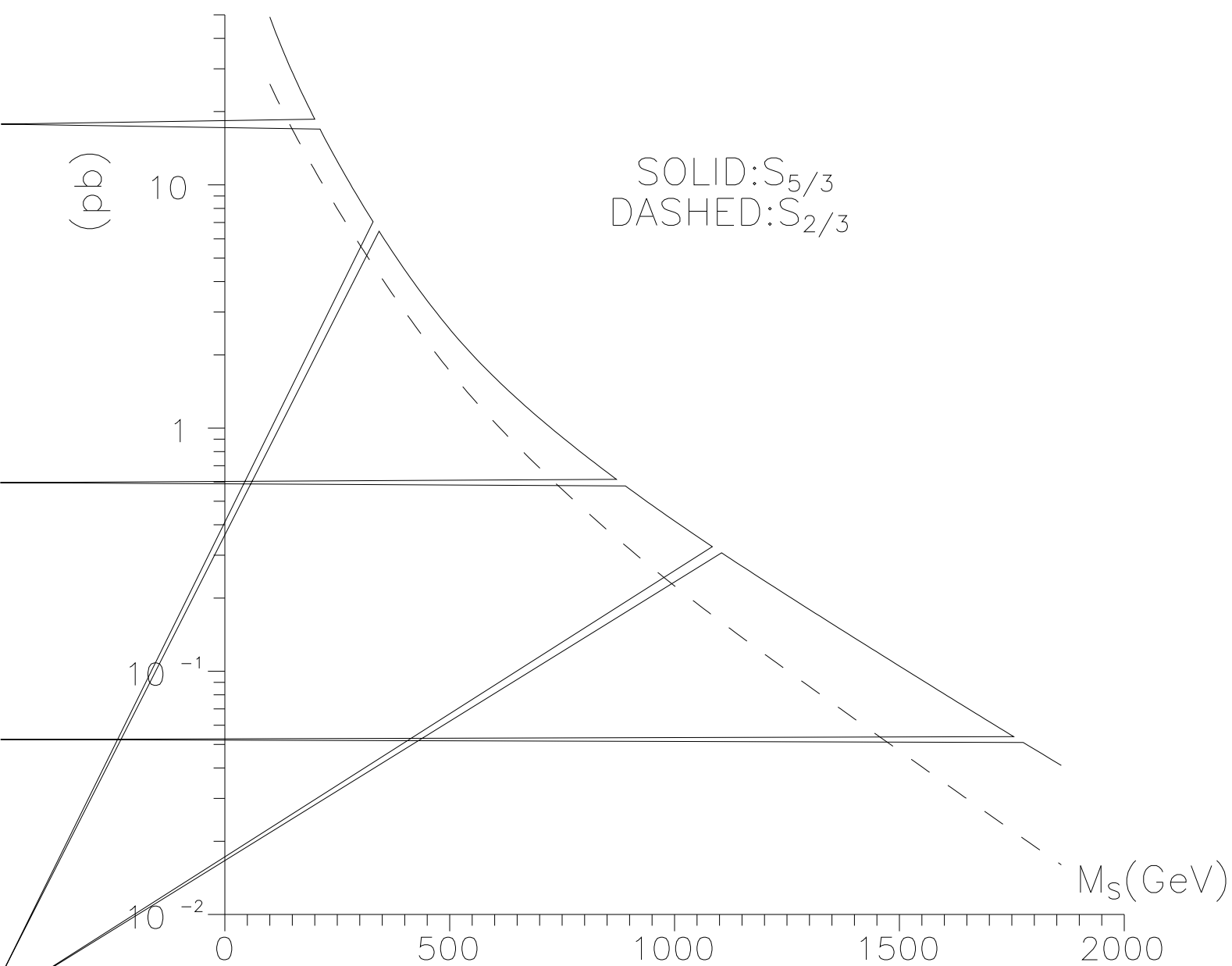


FIG. 4